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Wavelength Dependence of Cirrus Optical Depth

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14. ABSTRACT

The normalized wavelength-dependent optical depth of the two cirrus cloud models resident in MODTRAN 4 ("standard" and "subvisual") is computed along with the scattering and absorption components. The wavelength-dependent asymmetry parameter is also calculated. We find that the optical depths as a function of wavelength are significantly different for the two models, most of which is attributable to particle size effects.

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1. Introduction

Cirrus clouds[1] are frequently characterized by their optical depth at a specific wavelength, usually in the visible near 0.55 μm or at lidar wavelengths 0.6328 μm. For example, subvisual cirrus is defined as ".... any high clouds composed primarily of ice ... and whose vertical visible optical depth is 0.03 or less."[2] It is frequently necessary to know the optical depth at a different wavelength. In this report, we compute the optical depth as a function of wavelength for the two cirrus cloud models resident in MODTRAN 4 ("standard" and "subvisual").

The Moderate Resolution Transmittance (MODTRAN) code, developed by the Air Force Research Lab (AFRL), calculates atmospheric transmittance and radiance for frequencies (in wavenumbers) from 0 to 50,000 cm^{-1} at moderate spectral resolution, primarily 2 cm^{-1} (20 cm^{-1} in the UV).[3] The development of the MODTRAN model was motivated by the need for higher spectral resolution than was available in the Low-Resolution Transmittance (LOWTRAN7). MODTRAN's capabilities include spherical refractive geometry, solar and lunar source functions, scattering (Rayleigh, Mie, single and multiple), and default atmosphere profiles (gases, aerosols, clouds, fogs, and rain). MODTRAN version 4 release 1 is the most current release and was used for these calculations.

2. Calculations

The defining input parameters for both cirrus cloud models in MODTRAN4[4] are extinction coefficient K_E (km^{-1}), cloud thickness L (derived from the specified cloud base height and cloud top height), cloud base height, and choice of cloud model, standard or subvisual. The optical depth, τ, of the cloud is defined as

$$\tau = K_E L = (K_S + K_A) L, \tag{1}$$

where K_E is the extinction coefficient (km^{-1}), and L is the cloud thickness. K_S and K_A are the scattering and absorption components of K_E, respectively. τ is a unitless quantity.

The transmission, t, of the cloud is then given by

$$t = \exp(-K_E L) = \exp(-\tau). \tag{2}$$

The threshold optical depth for subvisual cirrus is 0.03, which corresponds to a transmission of 0.97. Note that when the optical depth is small, i.e., $\tau << 1$, then the series expansion reveals

$$t = 1 - \tau + \tau^2/2! - \tau^3/3! \approx 1 - \tau, \tag{3}$$

which handily reproduces $t \approx 0.97$ when $\tau = 0.03$.

Owing to particle size effects and variations of the index of refraction with wavelength, λ, τ also varies with wavelength. The wavelength dependence for K_E, K_A, and asymmetry are hard-coded into MODTRAN4 for both cirrus cloud models. These values were computed by Shettle et al. [5] based on Warren's optical constants[6] and Shettle et al.'s assumed particle size distribution given by the log-normal distribution function:

$$dN/d\mathit{a} = n(\mathit{a}) = \mathrm{a}\, \mathit{a}^{\alpha} \exp(-b\mathit{a}), \tag{4}$$

where a is the particle radius, and a, α, and b are constants. Figure 1 shows the particle size distributions used to compute K_E. The mean (mode) particle radius a for the standard and subvisual models is 64 μm and 4 μm, respectively, and the calculations were performed under the assumption that all the particles are spherical.

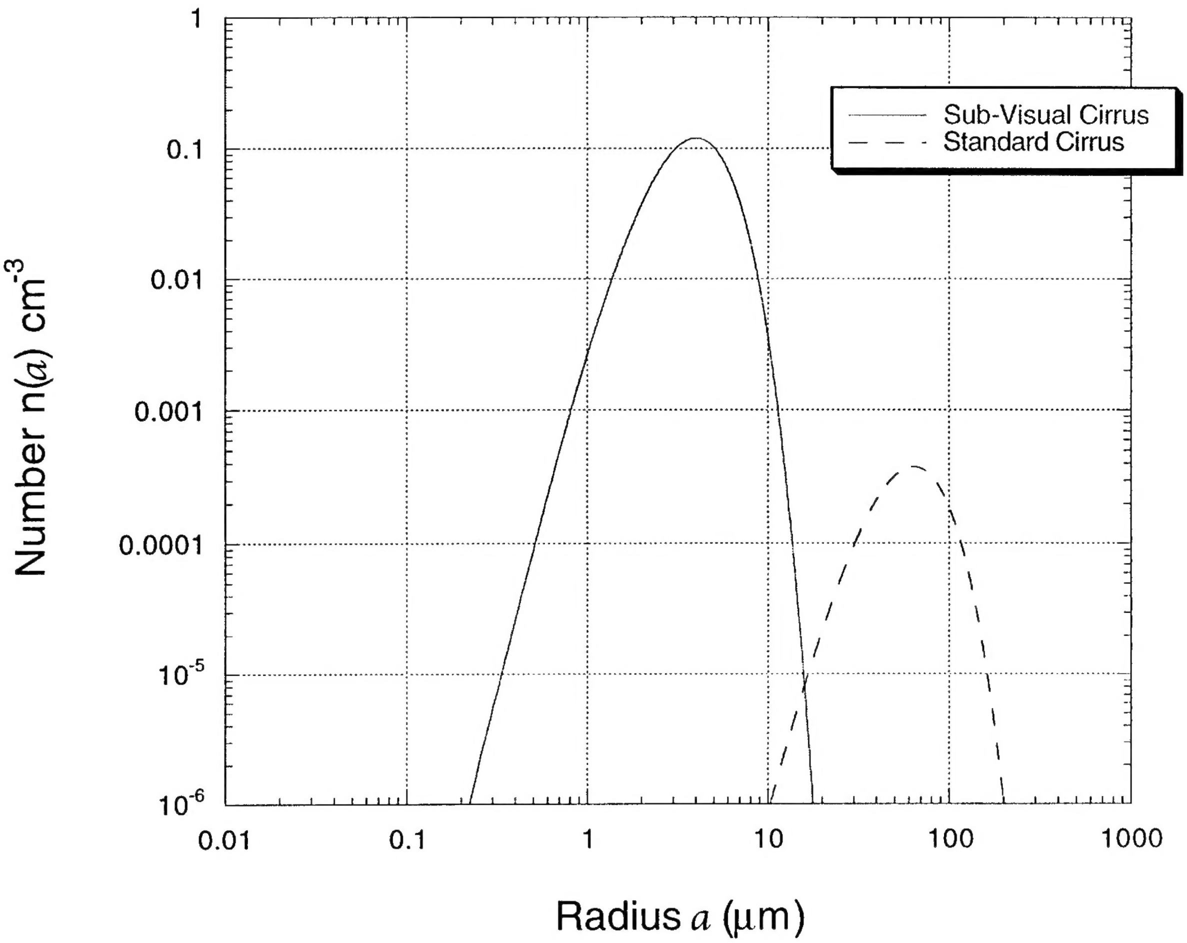

Figure 1. The particle size distribution for the subvisual model contains more particles cm^{-3}, and they are on average much smaller (a_{mode} = 4 µm) than for the standard model (a_{mode} = 64 µm).

Figure 2 shows the optical depth of both cloud models, normalized to unity at 0.55 µm, extracted from MODTRAN4. Since τ is proportional to K_E, this is essentially K_E normalized to unity at 0.55 µm. It is obvious that the standard model's optical depth varies very little with wavelength, but the subvisual model's optical depth varies considerably. The reason for this is relatively simple, and relates to the particles' optical depth.

Small particles tend to be optically thin, and the large particles tend to be optically thick. This is best expressed in terms of the scattering size parameter X $(= 2\pi a/\lambda)$[7,8] and the absorption size parameter Ω $(=4\pi k a/\lambda)$[9]. These values are shown in Table 1, which is calculated for the mode particle sizes 4 and 64 µm, using the optical constants of Warren.[6] Thus, the small particles' behavior is dominated by absorption, while the large particles' behavior is dominated by scattering. The composition of a large particle (X or $\Omega \gg 1$) is less important than its size because its extinction properties will be dominated by scattering. Extinction by small (optically thin, X or $\Omega \ll 1$) particles, on the other hand, is more sensitive to composition (optical constants) because the actual absorptions play a relatively larger role.

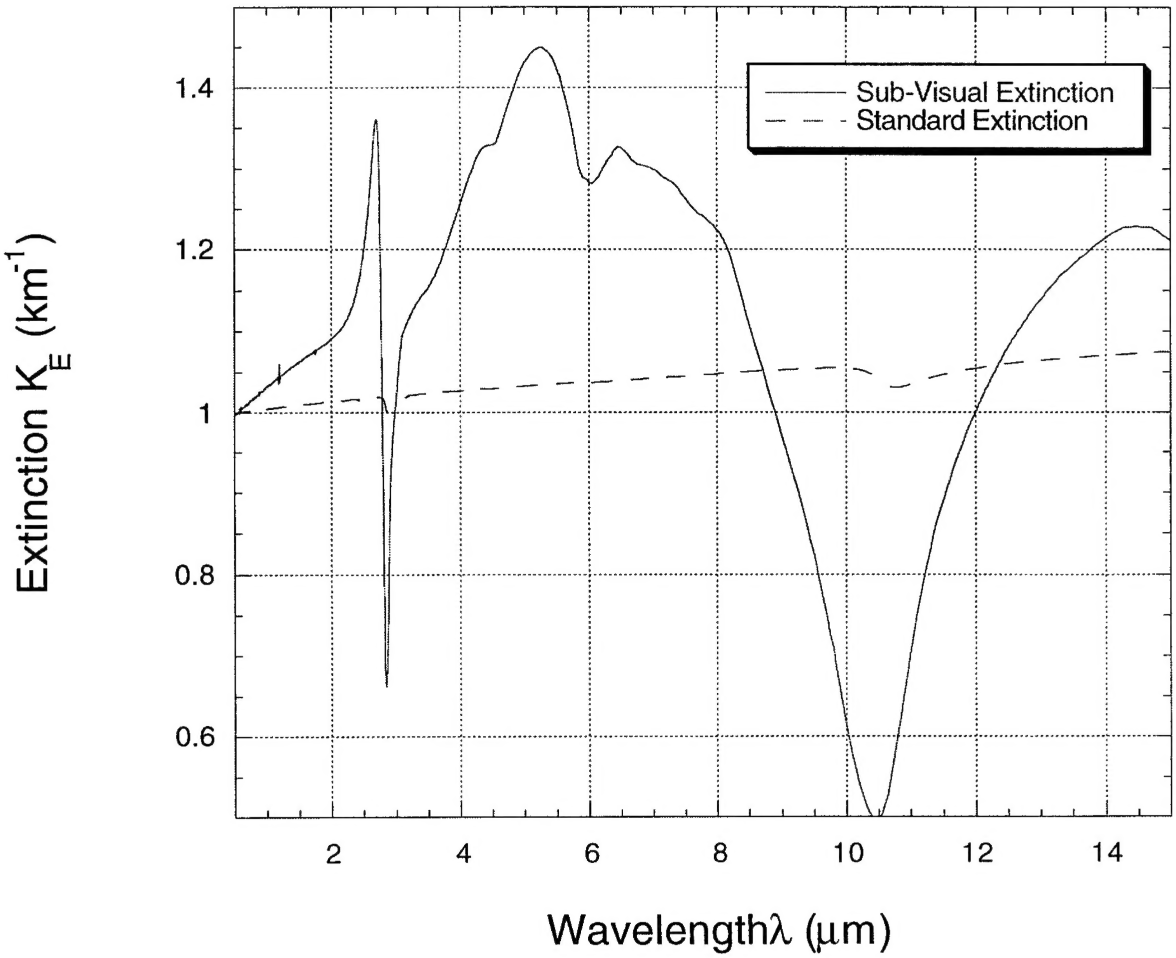

Figure 2. The extinction coefficient, K_E, for the subvisual model displays significantly more spectral structure than does the standard model. The values for K_E are normalized to unity at 0.55 μm.

Table 1. Scattering and Absorption Size Parameters for the Standard and Subvisual Cirrus Cloud Mode Particle Sizes in MODTRAN4

	a = 4 μm		a = 64 μm	
	subvisual (Ω<<1)		standard (X>>1)	
λ(μm)	X	Ω	X	Ω
2	13	0.01	201	0.19
4	6.3	0.02	100	0.3
6	4.2	0.27	67	4.3
8	3.4	0.07	50	1.2
10	2.5	0.08	40	1.4
12	2.1	0.32	33	5.2

The wavelength dependence of K_S and K_A for the subvisual cirrus model is shown in Figure 3, and that of the Standard cirrus model in Figure 4.

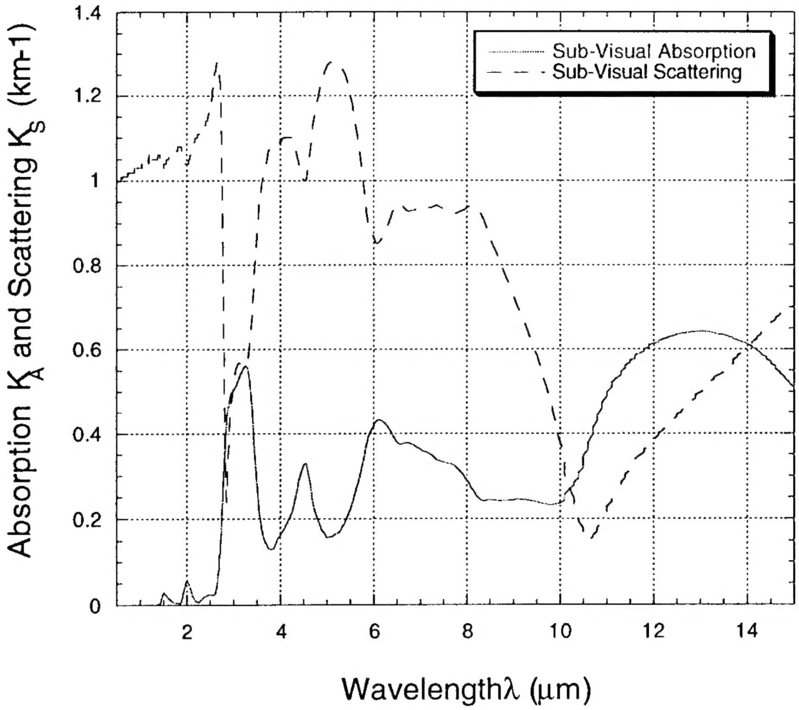

Figure 3. The components of extinction coefficient, K_E, (absorption K_A and scattering K_S) as a function of wavelength for the subvisual cirrus model in MODTRAN4.

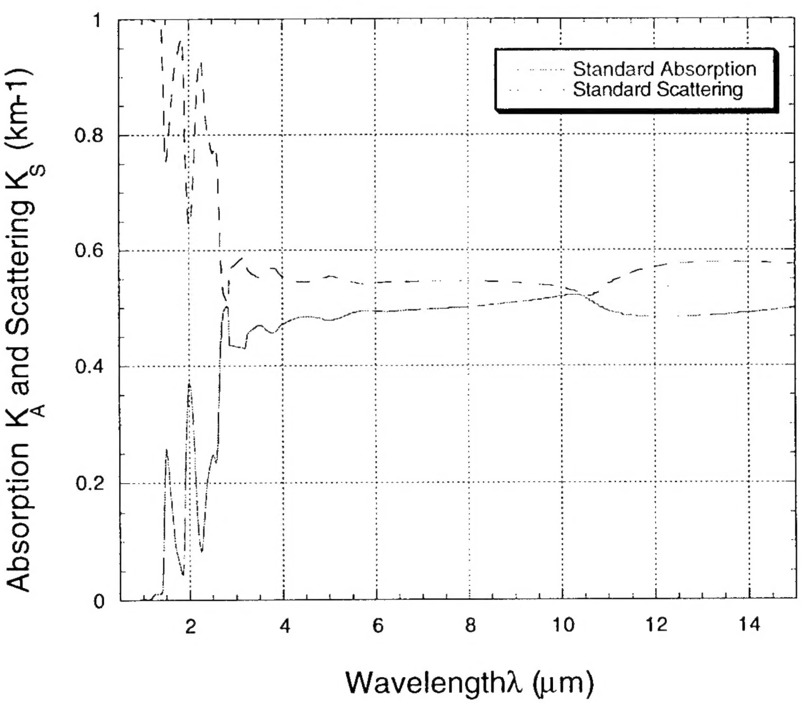

Figure 4. The components of the extinction coefficient, K_E, (absorption K_A and scattering K_S) as a function of wavelength for the standard cirrus model in MODTRAN4.

The asymmetry parameter ,g, characterizes the scattering of light for the particle as a whole. For pure forward scattering, g would be +1.0, and for pure backscattering, g would be –1.0. For a symmetric scatterer (like a Rayleigh scatterer), g would be zero. Figure 5 shows the asymmetry parameter, g. for both the standard and subvisual cirrus models as a function of wavelength. In both cases, g is between about 0.75 and 1.00, though the standard model is generally much closer to unity at all wavelengths. This is because the standard model has larger particles, and these are more efficient forward scatterers than the smaller particles that comprise the subvisual cirrus model.

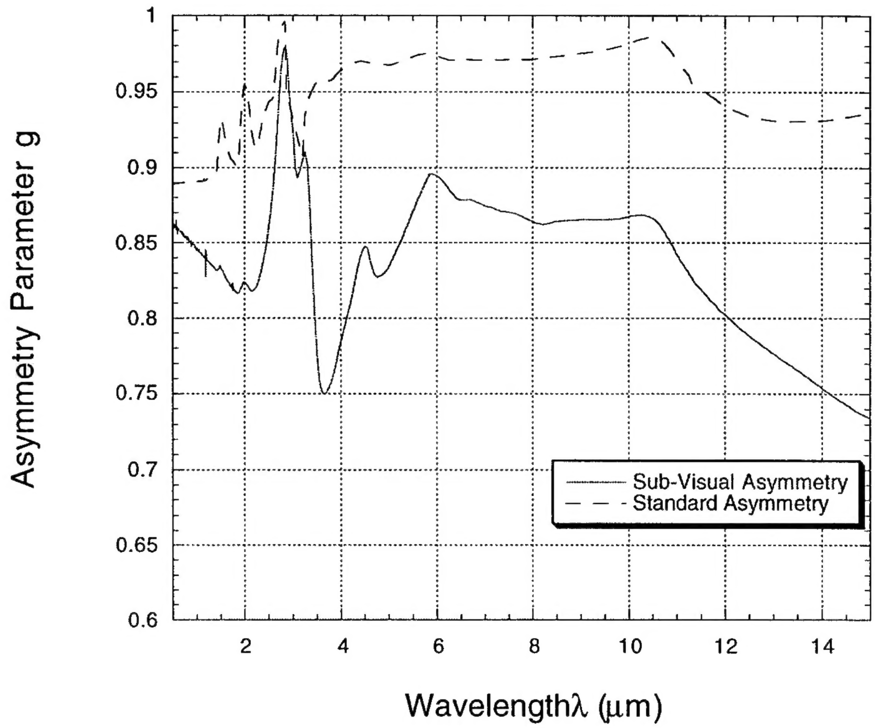

Figure 5. The asymmetry parameter, g, as a function of wavelength is between about 0.75 and 1.0 for both models. The values for both models are greater than 1, indicating that the particles are primarily forward scatterers.

3. Summary and Conclusions

The normalized wavelength-dependent optical depth of the two cirrus cloud models resident in MODTRAN 4 (“standard” and “subvisual”) has been presented and decomposed into its scattering and absorption components. We find that the optical depth as a function of wavelength is significantly different for the two models, most of which is attributable to particle size effects. The wavelength-dependent asymmetry parameter is also presented, and shows similar particle size effects.

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